

# STIRRED, NOT CLUMPED: EVOLUTION OF TEMPERATURE PROFILES IN THE OUTSKIRTS OF GALAXY CLUSTERS

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*The Astrophysical Journal, submitted*

## ABSTRACT

Recent statistical X-ray measurements of the intracluster medium (ICM) indicate that gas temperature profiles in the outskirts of galaxy clusters deviate from self-similar evolution. Using a mass-limited sample of galaxy clusters from cosmological hydrodynamical simulations, we show that the departure from self-similarity can be explained by non-thermal gas motions driven by mergers and accretion. Contrary to previous claims, gaseous substructures only play a minor role in the temperature evolution in cluster outskirts. A careful choice of halo overdensity definition in self-similar scaling mitigates these departures. Our work highlights the importance of non-thermal gas motions in ICM evolution and the use of galaxy clusters as cosmological probes.

*Subject headings:* cosmology: theory — galaxies: clusters: general — galaxies: clusters : intracluster medium — methods : numerical — X-rays:galaxies:clusters

## 1. INTRODUCTION

The outskirts of galaxy clusters mark the transition from the cosmic web to the intracluster medium (ICM), where cosmic filaments feed into the gravitational potential well of the galaxy cluster. Measurements of gas properties in cluster outskirts directly probe the formation of these structures and physical mechanisms that affect the ICM. A thorough understanding of these mechanisms at all radii will further enable cluster cosmology.

The use of clusters as cosmological probes hinges on our ability to tightly constrain the evolution of the galaxy cluster mass function, which is sensitive to cosmological parameters (see Allen et al. 2011, for a review). We can exploit self-similar properties of galaxy clusters to establish relationships between directly observable properties and the galaxy cluster mass (see Voit 2005; Kravtsov & Borgani 2012, for a review).

The ICM radial profiles of self-similar galaxy clusters resemble one another when rescaled with respect to mass and redshift dependent quantities. When radially integrated, profile quantities can serve as a proxy of cluster mass. The self-similar model of galaxy clusters is based on simplifying assumptions. In reality these assumptions are broken in our universe’s cosmology and through non-gravitational baryonic processes, such as radiative cooling and star formation. The only way to directly probe and exploit self-similar relations is to self-consistently model galaxy cluster formation and calibrate observable-mass relations used by observations. To mitigate complications from baryonic physics that dominate the cluster cores, observations have pushed to cluster outskirts to potentially recapture self-similar behavior. Evidence, however, points to the contrary.

First, X-ray measurements show that the ICM entropy profiles break from the self-similar power-law scaling with radius at large radii (e.g. George et al. 2009; Bautz et al. 2009; Reiprich et al. 2009; Hoshino et al. 2010; Kawaharada et al. 2010; Akamatsu et al. 2011; Okabe et al. 2014) contradicting theoretical predictions (Tozzi & Norman 2001; Voit et al.

2005). Next, the observational analysis of McDonald et al. (2014) presents evidence of a non-self-similar evolution of ICM properties at radii larger than  $R_{500c}$ . With *Chandra* data of 80 galaxy clusters selected from the *South Pole Telescope* (SPT) survey, they found that the outskirts of high redshift clusters have cooler scaled temperatures than low redshift clusters. The origin of the observed temperature evolution is well not understood.

To address the first finding, detailed X-ray observations with *Suzaku* (Simionescu et al. 2011; Walker et al. 2013; Urban et al. 2014) and *ROSAT* (Eckert et al. 2012, 2013) provided evidence that density inhomogeneities in the ICM likely break self-similar entropy profiles (but see Okabe et al. 2014, for a different explanation). In support of observational evidence, cosmological simulations showed that gas in cluster outskirts are highly clumpy (Nagai & Lau 2011; Roncarelli et al. 2013; Vazza et al. 2013). This clumpiness boosts the X-ray surface brightness, leading to overestimates in gas densities and underestimates in entropy (Avestruz et al. 2014). Such ICM inhomogeneities are associated with overdense infalling substructures such as subhalos and penetrating filaments (Battaglia et al. 2015; Lau et al. 2015).

To extend clumping effects to the second finding, McDonald et al. (2014) proposed that the presence of more accreting group size halos at higher redshifts drives the evolution of the scaled outskirts temperatures, an effect called “super-clumping”. This interpretation is based on the fact that mass accretion rates and merger frequencies increase with redshift (e.g., Wechsler et al. 2002; Fakhouri & Ma 2009; Tillson et al. 2011), and that group size halos substructures have lower virial temperatures than host cluster ICM. At high redshift, these substructures are usually too dim for X-ray observations to identify and mask out.

On the other hand, a significant fraction of outskirts gas does not reside in these dense substructures. Rather, much of the outskirts gas exists in the form of low density, diffuse gas (e.g., Zhuravleva et al. 2013). In the outskirts, accretion shocks con-

vert kinetic energy of infalling gas to thermal energy. However, not all of the kinetic energy is thermalized by the shocks. The residual gas motions slowly thermalize through turbulent dissipation at the dynamical timescale (Shi & Komatsu 2014). As a result, clusters that experience more recent gas accretion have less time to thermalize and tend to have a higher fraction of energy in the form of non-thermal gas motions (Lau et al. 2009; Vazza et al. 2011; Nelson et al. 2012; Shi et al. 2015). Therefore, the ICM temperature evolution can also depend on the rate at which these gas motions thermalize.

The aim of this work is to understand the physical mechanisms that contribute to the observed non-self-similar evolution of temperature profiles in cluster outskirts from the X-ray observations of the *Chandra*-SPT cluster sample by McDonald et al. (2014). We use a mass-limited sample of galaxy clusters from a cosmological hydrodynamical simulation. Our sample is comparable in mass and redshift range to the observed cluster sample. We demonstrate that non-thermal gas motions in clusters is the dominant contributor to the observed temperature evolution in cluster outskirts. Substructure evolution plays a subdominant role, in contrast to the original interpretation by McDonald et al. (2014).

Our paper is organized as follows. We overview the notions of self-similarity in Section 2.1 and define ICM quantities of interest in Section 2.2. In Section 3 we briefly describe the simulation and the radial profile averaging. We present our results in Section 4, and our summary and discussions in Section 5.

## 2. THEORETICAL FRAMEWORK

### 2.1. Self-similar model

The standard self-similar model by Kaiser (1986) describes the properties of galaxy clusters based on their mass and redshifts. This Kaiser model is based on several simplifying assumptions about the formation of galaxy clusters. First, galaxy clusters form from scale-free gravitational collapse of the initial density perturbations in an  $\Omega_m = 1$  universe. Second, the amplitude of initial density fluctuation is scale-free; i.e., the matter power spectrum is a power law with  $P(k) \propto k^n$ . Finally, there are no additional physical processes that introduce any scale dependence. The scale-free setup of this problem defines a self-similar model where halo properties depend only on the slope and normalization of the initial density field at collapse.

Assuming further that the cluster gas is spherically symmetric and is in hydrostatic equilibrium with the cluster's gravitational potential well, we can define a characteristic temperature  $T_\Delta$ , which relates to the cluster mass as,

$$T_\Delta \propto \frac{GM_\Delta}{R_\Delta} \propto (\Delta \rho_r)^{1/3} M_\Delta^{2/3}. \quad (1)$$

Here,  $M_\Delta$  is the mass enclosed within a sphere of radius,  $R_\Delta$ , both defined with respect to some reference density  $\rho_r$  such that,

$$M_\Delta = \frac{4\pi}{3} R_\Delta^3 \Delta \rho_r(z), \quad (2)$$

and  $\Delta$  is the mean overdensity contrast with respect to a reference density,  $\rho_r(z)$ , at a given redshift  $z$ . The characteristic temperature is then a function of cluster mass and redshift  $T_\Delta \equiv T_\Delta(M_\Delta, z)$ .

The temperature profile can be then scaled with respect to

this characteristic temperature as,

$$\tilde{T}(r/R_\Delta) \equiv \frac{T(r/R_\Delta)}{T_\Delta(M_\Delta, z)}. \quad (3)$$

If galaxy clusters were perfectly self-similar under this scaling, the shape and normalization of  $\tilde{T}(r/R_\Delta)$  would be independent of the cluster mass and redshift.

It is important to note that a mass-limited sample of real galaxy clusters do not satisfy *any* of the assumptions of the Kaiser model, but have nonetheless empirically exhibited near self-similar behavior. We therefore explore physical effects that lead to observed deviations from self-similar scaling in a similarly representative sample.

Note that the self-similar model depends on which overdensity is used to define cluster mass and radius in Equation (2). A commonly used density contrast in cluster measurements is  $\Delta = 500c$ , where  $c$  denotes the overdensity defined with respect to the critical density of the universe. We additionally consider several different characteristic overdensities  $\Delta = 200c, 500c, 1600c$  and  $\Delta = 200m, 500m, 1600m$ , where  $m$  denotes the overdensity defined with respect to the mean mass density of the universe. Note that these overdensities are redshift dependent; e.g.,  $\Delta = 1600m$  approximately corresponds to  $\Delta = 500c$  at  $z = 0$ .

### 2.2. Thermal, Non-thermal and Total Energy Contents of the ICM

Energy content of the ICM consists of thermal and non-thermal components, where the latter arises primarily from random gas motions generated by mergers and accretion events. We can define the “total” temperature as the sum of specific kinetic and internal energies of the gas, as it incorporates both thermal and non-thermal motions of the gas,

$$T_{\text{tot}} \equiv T_{\text{mw}} + T_{\text{nt}}, \quad (4)$$

where  $T_{\text{mw}}$  is the mass-weighted temperature and  $T_{\text{nt}}$  is the “non-thermal temperature” defined as,

$$k_b T_{\text{nt}} \equiv \frac{1}{3} \mu m_p \langle v_{\text{gas}}^2 \rangle_{\text{mw}}, \quad (5)$$

where  $k_b$  is the Boltzmann constant,  $\mu = 0.59$  is the mean molecular weight of the ionized ICM,  $m_p$  is the proton mass, and  $\sqrt{\langle v_{\text{gas}}^2 \rangle_{\text{mw}}}$  is the 3-dimensional mass-weighted root-mean-square velocity of the gas. Physically, this “non-thermal temperature”  $k_b T_{\text{nt}}$  represents the specific kinetic energy associated with gas motions in the ICM.

The total temperature for a virialized gas is analogous to the velocity dispersion of a halo, which is in local Jeans equilibrium with the gravitational potential of the halo (Diemer et al. 2013). The circular velocity profile, a proxy for the potential, evolves self-similarly when scaled with respect to the critical density of the universe (Diemer & Kravtsov 2014; Lau et al. 2015). This follows from the fact that gravitational potential wells of galaxy clusters are set early in their history (e.g., van den Bosch et al. 2014) and evolve slowly. Therefore, the total temperature profile within near virialized regions should exhibit the same scaling as the circular velocity profile. Note that the thermal temperature would only exhibit this scaling if the cluster were in perfect hydrostatic equilibrium.

## 3. METHODOLOGY

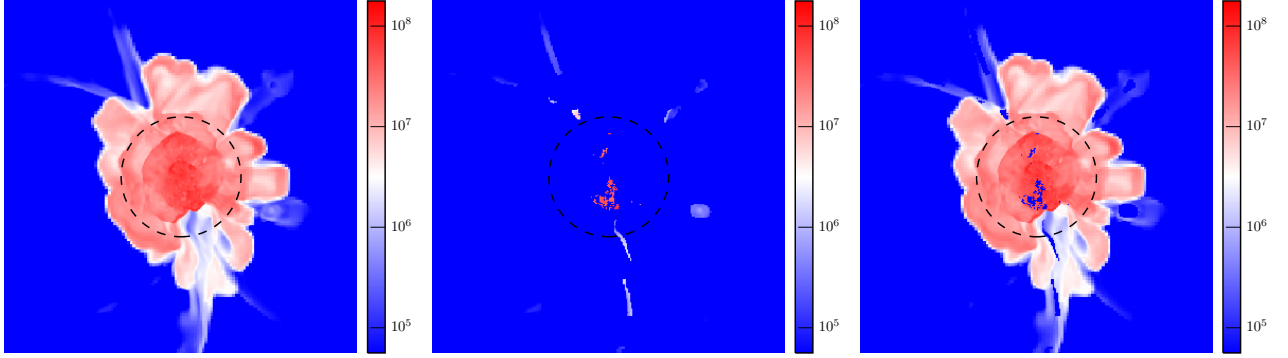


FIG. 1.— Projected mass-weighted temperature  $T_{\text{mw}}$  maps of one of the  $z = 0$  clusters selected from the sample. From *left to right*: map of the total gas, substructures (clump and filaments), and “bulk” gas (i.e., without substructures). The dimension for each panel is  $15.6 h^{-1} \text{Mpc} \times 15.6 h^{-1} \text{Mpc}$ , with depth of  $1.9 h^{-1} \text{Mpc}$ . The circle in dashed line shows  $3R_{500c} = 2.6 h^{-1} \text{Mpc}$  of the cluster. The color bars show the temperature scales in Kelvin.

### 3.1. Cosmological Simulation

We use galaxy clusters extracted from the *Omega500* simulation (Nelson et al. 2014b). The *Omega500* simulation is a cosmological hydrodynamical simulation performed with the Adaptive Refinement Tree code (Kravtsov 1999; Kravtsov et al. 2002; Rudd et al. 2008). The simulation box has a comoving length of  $500 h^{-1} \text{Mpc}$ , resolved using a uniform  $512^3$  root grid and 8 levels of mesh refinement, with maximum comoving spatial resolution of  $3.8 h^{-1} \text{kpc}$ .

We analyze a mass-limited sample of 65 galaxy clusters with  $M_{500c} \geq 3 \times 10^{14} h^{-1} M_{\odot}$  at  $z = 0.0$  and their progenitors at  $z = 0.3, 0.5$ , and  $0.7$  to match the *Chandra*-SPT sample of McDonald et al. (2014). We then measure the average evolution of thermodynamic profiles in our sample.

Initial cluster identification uses a spherical overdensity halo finder described in Nelson et al. (2014b). The final cluster sample is from a re-simulated box with higher resolution dark matter particles in regions of the identified clusters. This “zoom-in” technique results in an effective mass resolution of  $2048^3$ , corresponding to a dark matter particle mass of  $9 \times 10^8 h^{-1} M_{\odot}$  inside a spherical region with cluster-centric radius of three times the virial radius for each cluster. Further details of the simulation can be found in Nelson et al. (2014b).

Since cluster core physics are not expected to significantly affect cluster outskirts, we present our main results using the *Omega500* simulation with non-radiative (NR) gas physics. In order to assess the effects of baryonic physics, we also analyze the outputs of the *Omega500* re-simulation with radiative cooling, star formation, and supernova feedback based on the same sub-grid model of galaxy formation described in Nagai et al. (2007a).

### 3.2. Averaged Radial Profiles

We compute average radial profiles by dividing the gas volume of a galaxy cluster halo into 99 concentric spherical shell bins centered around the minimum of the gravitational potential. Throughout this work, we use the equally spaced logarithmic spacing in the comoving radial distance from  $10 h^{-1} \text{kpc}$  to  $10 h^{-1} \text{Mpc}$ .

We compute average temperature profile of each simulated galaxy cluster as,

$$T_w(r_i) = \frac{\sum_j w_{ij} T_{ij} \Delta V_j}{\sum_j w_{ij} \Delta V_j}, \quad (6)$$

where  $\Delta V_{ij}$  is the volume occupied by the hydro cell  $j$  in the radial bin  $i$ ,  $T_{ij}$  is the temperature of the gas cell, and  $w_{ij}$  is the “weight” for the averaging.

We adopt two different weighting schemes. First, we compute mass-weighted temperature profile  $T_{\text{mw}}$ , with the weight set to the gas mass density of the hydro cell  $w_{ij} = \rho_{g,ij}$ . Physically, the mass-weighted temperature corresponds to the specific internal energy of the cluster gas.

Second, we compute the spectral-temperature  $T_{\text{sp}}$ , which is the average temperature using X-ray emission as weights:

$$w_{ij} = \rho_{g,ij}^2 \Lambda_{\text{eff}}(T_{ij}, Z_{ij} = 0.3 Z_{\odot}) \quad (7)$$

where  $\Lambda_{\text{eff}}$  is the effective cooling function in the  $0.5 - 2.0 \text{ keV}$  energy band using the MEKAL (Liedahl et al. 1995) plasma code, weighted by the effective area of the *ACIS-I* CCD on *Chandra* X-ray telescope. Since the X-ray emission in the  $0.5 - 2.0 \text{ keV}$  energy range is not very sensitive to the adopted metallicity, we assume constant abundance of  $Z = 0.3$  solar throughout.

Finally, using the self-similar scaling defined by Equation (3), we normalize each galaxy cluster profile,

$$\tilde{T}(r/R_{500c}) = \frac{T(r/R_{500c})}{T_{500c}}, \quad (8)$$

where  $T_{500c} \equiv GM_{500c}/(2R_{500c})$ . We then calculate the average  $\tilde{T}$  in each redshift in order to assess the departure of the *average normalized temperature profile* from self-similar evolution.

### 3.3. Decomposition of Diffuse and Clumpy Components

To assess the effects of gas clumping on the X-ray emissions, we decompose the ICM into the diffuse and clumpy components using the method described in Zhuravleva et al. (2013). The probability distribution function (PDF) of the density in each shell follows a log-normal distribution with a high density tail. We exclude small scale gas clumps, infalling subhalos, and penetrating filaments by removing gas that have density higher than  $2\sigma$  from the median of the density PDF in each radial bin.

We denote the profiles calculated with or without denser substructures using the subscripts, “all” or “bulk”, respectively. The mass-weighted temperature profile with (or without) substructures is labeled by  $T_{\text{mw,all}}$  (or  $T_{\text{mw,bulk}}$ ). Figure 1

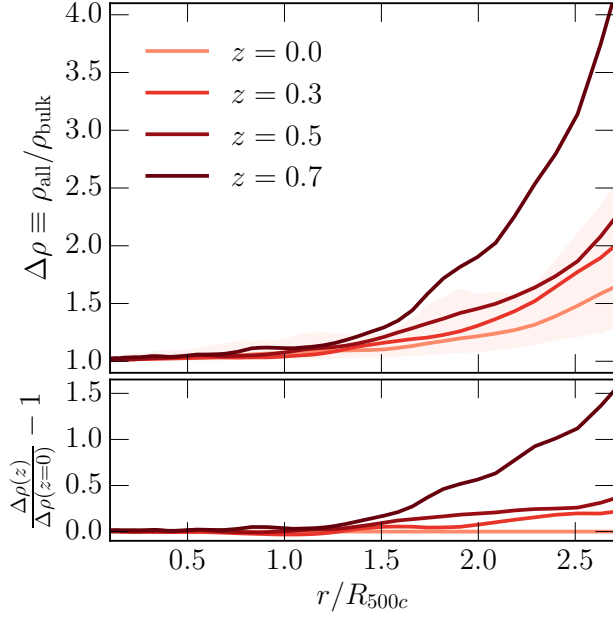


FIG. 2.— Top panel: Ratio of the average density profile of all gas to that of the bulk component (without substructures),  $\Delta\rho \equiv \rho_{\text{all}}/\rho_{\text{bulk}}$ , at different redshifts as a function of the cluster-centric radius for simulated clusters at  $z = 0.0, 0.3, 0.5, 0.7$ . The shaded region corresponds to the  $1\sigma$  spread about the mean profile at  $z = 0$ . The bottom panel shows the fractional difference between the profile at each redshift to the profile at  $z = 0$ .

illustrates the mass-weighted temperature maps for one of the simulated clusters including all gas, substructures, and bulk diffuse components (see Figure 1 in Lau et al. 2015, for the corresponding projected gas density maps).

#### 4. RESULTS

In this work, we investigate physical mechanisms that contribute to the evolution of scaled thermal temperature profiles in the outskirts of galaxy clusters. These mechanisms include the evolution of overdense gas substructures, non-thermal gas motions, growth of the cluster halo with respect to the defined reference overdensity, non-equilibrium physics, and baryonic cooling and star formation. With a mass-limited simulated cluster sample, we assess the relative importance of factors that influence temperature profiles in galaxy cluster outskirts.

##### 4.1. Evolution of Substructures

We first examine the contribution of substructures on the evolution of the gas density profiles. The top panel of Figure 2 shows the ratio of the average density profile of all gas to that of the bulk component (without substructures),  $\Delta\rho \equiv \rho_{\text{all}}/\rho_{\text{bulk}}$ , at different redshifts. We normalize the radial range of all profiles using  $R_{500c}$  of each cluster before computing the average profiles of the cluster sample at each redshift. The lower panel shows the fractional deviation of the gas density ratio at high redshifts relative to  $z = 0$ .

At all redshifts, we find that the bulk component comprises more than 90% of the gas at  $r \lesssim R_{500c}$ , while the contribution of substructures increases with radius at  $r \gtrsim R_{500c}$ . The contribution of gaseous subhalos and filaments are more prominent in the outskirts of galaxy clusters. We also find that the contribution of dense substructures increases with redshift. For example, the substructures comprise  $\approx 50\%$  of the total gas density at  $r/R_{500c} = 2$  at  $z = 0.7$ , while their contribution is only  $\approx 20\%$  at  $z = 0$ . High redshift clusters contain an en-

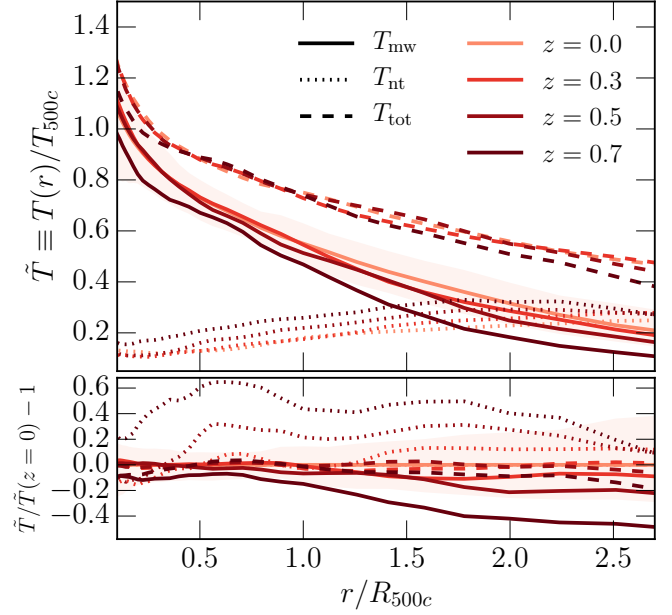


FIG. 3.— Top panel: Solid lines correspond to the average normalized mass weighted gas temperature profile,  $\tilde{T}_{\text{mw}}$ , at  $z = 0.0, 0.3, 0.5, 0.7$ . The shaded region shows the  $1\sigma$  spread for the  $z = 0$  sample. The dotted lines correspond to the average normalized non-thermal temperature,  $\tilde{T}_{\text{nt}}$ , defined in Equation 5. The dashed lines correspond to the sum of the two temperatures at each redshift,  $\tilde{T}_{\text{tot}} = \tilde{T}_{\text{mw}} + \tilde{T}_{\text{nt}}$ . Bottom panel: Solid (dashed or dotted) lines show the difference in the ratios for between each thermal (total on non-thermal) average temperature profile to the  $z = 0$  average profile. The normalized  $\tilde{T}_{\text{mw}}$  profiles have a clear systematic evolution outside of  $r/R_{500c} \gtrsim 0.5$  that breaks self-similarity. High redshift clusters have cooler outskirts. The trend is reversed for  $\tilde{T}_{\text{nt}}$ . The total temperature, however, maintains a self-similar behavior at all radii with no indication of a systematic evolution. The thermal temperature evolution is due to the fact that clusters at higher redshifts are dynamically younger with gas that has not fully thermalized.

hanced level of substructures compared to the low redshift counterparts.

##### 4.2. Evolution of ICM Temperatures

Next, we examine the role of the non-thermal gas motions on the evolution of temperature profiles. The solid lines in the top panel of Figure 3 show the average radial profile of the normalized mass-weighted temperature,  $\tilde{T}_{\text{mw}}$ , at  $z = 0.0, 0.3, 0.5$ , and  $0.7$ . The solid lines in the bottom panel of Figure 3 show the difference between  $\tilde{T}_{\text{mw}}$  at each redshift to that of  $z = 0$ :  $\Delta\tilde{T}_{\text{mw}} \equiv \tilde{T}_{\text{mw}}(z)/\tilde{T}_{\text{mw}}(z=0) - 1$ . Note that  $\Delta\tilde{T}_{\text{mw}} \approx 0$  would indicate that the cluster sample exhibits self-similar evolution with this scaling.

The magnitude of  $\Delta\tilde{T}_{\text{mw}}$  systematically increases with redshift in cluster outskirts. For example,  $\Delta\tilde{T}_{\text{mw}}$  at  $r/R_{500c} \gtrsim 1.5$  is  $\sim 30\%$  between  $z = 0.0$  to  $z = 0.7$ , and  $\sim 10\%$  between  $z = 0.0$  to  $z = 0.5$ . These evolutionary trends are consistent with the results of the recent *Chandra* measurements (McDonald et al. 2014).

The dotted lines in Figure 3 show the average normalized profiles of the non-thermal temperature,  $\tilde{T}_{\text{nt}}$ , at each redshift. At all redshifts,  $\tilde{T}_{\text{nt}}$  increases with radius and exceeds  $\tilde{T}_{\text{mw}}$  at  $2 \lesssim r/R_{500c} \lesssim 4$ . The crossover occurs at smaller cluster-centric radii for higher redshift clusters, when the potential well also extends to a smaller radius. This result is consistent with a physical picture that gas motions generated by mergers

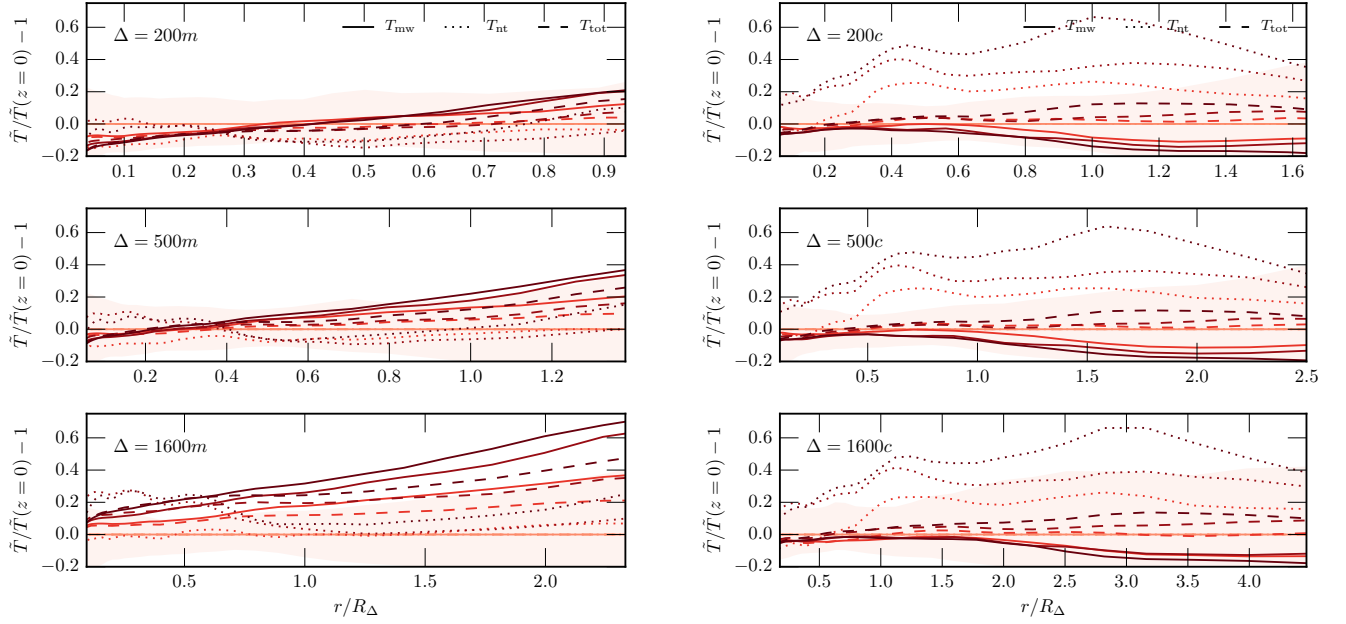


FIG. 4.— Same as the lower panel in Figure 3 but for different overdensities. From top to bottom:  $\Delta = 200$ , 500, and 1600. The left column corresponds to overdensities with respect to the mean density of the universe, denoted with  $m$ , and the right with respect to the critical density of the universe, denoted with  $c$ . The radial scales are chosen such that each overdensity probes approximately the same radial range  $0.1 \leq r/R_{500c} \leq 2.7$  at  $z = 0$ . The scaling with respect to  $\Delta = 200m$  best captures the evolution in thermalization state of the gas in the outskirts; the mass-weighted temperature exhibits the most self-similar evolution with this choice of  $\Delta$ .

and accretion events are gradually converted into the kinetic energy through shocks and turbulent dissipation at smaller radii. Since the timescale of turbulent dissipation is shorter in the dense, inner regions of galaxy clusters (Shi & Komatsu 2014), a larger fraction of the merger or accretion driven gas motions have thermalized (Yu et al. 2015). The timescale difference leads to monotonically increasing (decreasing) thermal (non-thermal) temperature profiles.

Furthermore, we find a significant redshift evolution in  $\tilde{T}_{nt}$ . At  $r/R_{500c} \approx 1.5$ ,  $\tilde{T}_{nt}$  increases by 40% between  $z = 0.0$  and  $z = 0.7$ . High redshift clusters have a higher level of the normalized non-thermal temperature than low redshift clusters, because high redshift clusters are dynamically younger with more active gas accretion events (Nelson et al. 2014a).

The dashed lines in the top panel of Figure 3 show the average total temperature profiles in each redshift bin, which exhibit a remarkable degree of self-similar evolution at large radii, unlike the non-thermal and thermal temperature profiles.

We conclude that the evolution in the scaled thermal temperature profile is driven primarily by the thermalization process of the cluster gas where merger and accretion induced gas motions gradually convert into the thermal energy component of the ICM.

#### 4.3. Dependence on Halo Overdensity Definition

In this section, we highlight that the departure from the self-similarity depends on the definition of halo mass and radius. Figure 4 shows the normalized mass-weighted, non-thermal, and total temperature profiles,  $\Delta\tilde{T} \equiv \tilde{T}(z)/\tilde{T}(z=0) - 1$ , for different overdensity values:  $\Delta = 1600, 500$ , and 200 defined with respect to the mean density (left panels) and the critical density of the universe (right panels). The range of the  $x$ -axis in each panel shows the same physical radii corresponding to the radial range of  $0.1 < R/R_{500c} < 2.7$  at  $z = 0$ .

The left panel of Figure 4 shows that the different choices of reference densities with respect to the mean density results in varying degree of self-similar evolution in the ICM. Specifically, we find that the departure from the self-similar model diminishes for the smaller values of  $\Delta_{\text{mean}}$ . For example, the largest departure from the self-similar model is found for the largest mean overdensity of  $\Delta = 1600m$ , where the difference in the temperature at  $R_{1600m}$  (which roughly corresponds to  $R_{500c}$  at  $z = 0$ ) is about 30%. At  $r/R_{500m} = 0.6$  in the second panel, the normalized temperature decreases by  $\sim 10\%$  from  $z = 0.7$  to  $z = 0$ . At  $r/R_{200m} = 0.4$  in the third panel, the evolution is even smaller (at the level of  $\sim 5\%$ ). Our results suggest that the overdensity of  $\Delta = 200m$  works best, because  $R_{200m}$  tracks the average evolution of the radial location of the accretion shock (Lau et al. 2015; Shi 2016), where the bulk of thermalization process of the ICM occurs.

The right panel of Figure 4, on the other hand, illustrates that the choice of different overdensities with respect to the critical density does not significantly affect the evolutionary trends in the inner regions,  $r \lesssim R_{500c}$ , because the critical density evolves slowly after  $z \lesssim 1$  and tracks the evolution of the gravitational potential in the inner regions. The gas beyond this radial range is less thermalized especially at high redshifts due to the enhanced mass accretion, evidenced by the higher normalization of the non-thermal temperature profiles (indicated by dotted lines). The total temperature (indicated by dashed lines), on the other hand, remains self-similar with the difference of order 10% between  $z = 0.7$  and  $z = 0$ .

#### 4.4. Effects of Substructures

We quantify the effects of substructures on the temperature evolution by comparing the average temperature profile, normalized to  $T_{500c}$ , with and without excluding high density gas in infalling subhalos and filaments.

The solid lines in Figure 5 correspond to the ratios of  $T_{\text{mw,all}}$ ,



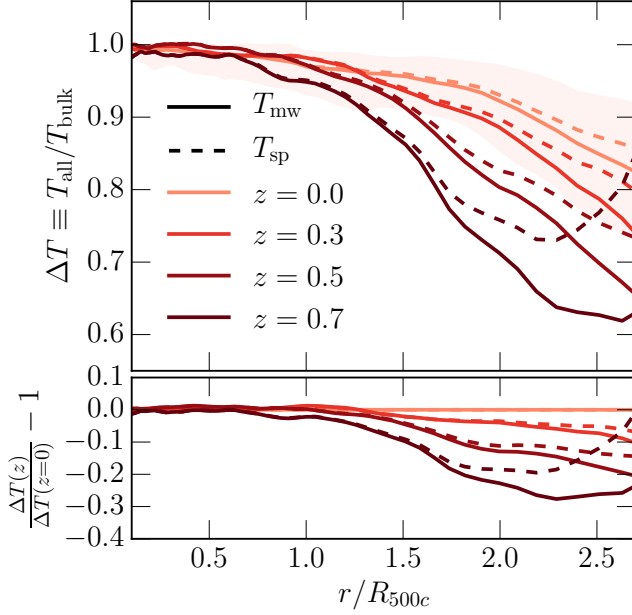


FIG. 5.— Top: Solid lines show the ratio of the mass-weighted temperatures  $T_{\text{mw}}$  of all gas to that of the substructure excluded “bulk” gas component at  $z = 0.0, 0.3, 0.5, 0.7$ . The dashed lines show the same ratio for the spectral-weighted temperature  $T_{\text{sp}}$ . Bottom: Difference in the ratios of the temperature profiles with  $z = 0$ .

the normalized mass-weighted temperature of all gas, and  $T_{\text{mw,bulk}}$ , the normalized mass-weighted temperature of the substructure-excluded bulk component. Each line color corresponds to the average profile at  $z = 0.0, 0.3, 0.5$ , and  $0.7$  for our simulated cluster sample. The ratio  $\Delta T_{\text{mw}} = T_{\text{mw,all}}/T_{\text{mw,bulk}}$ , is less than unity at all radii and all redshifts because the dense gas associated with substructures is typically cooler than the diffuse gas. At  $r/R_{500c} = 2$ ,  $\Delta T_{\text{mw}}$  is 92% at  $z = 0$ .  $\Delta T_{\text{mw}}$  decreases with redshift, reaching 70% at  $z = 0.7$ .

The dashed lines in the top panel of Figure 5 show the ratio  $\Delta T_{\text{spec}} = T_{\text{spec,all}}/T_{\text{spec,bulk}}$ , the spectral-weighted temperature ratios at  $z = 0.0, 0.3, 0.5$ , and  $0.7$ . Within  $r/R_{500c} < 1.5$ ,  $\Delta T_{\text{sp}}$  are nearly identical to those of  $\Delta T_{\text{mw}}$  at all redshifts. At larger radii,  $\Delta T_{\text{sp}}$  is larger and evolves less than  $\Delta T_{\text{mw}}$ .

The  $\Delta T_{\text{sp}}$  profiles indicate that spectral weighting leads to the average of all of the gas to be more similar to the bulk component. Spectral weighting has both a temperature and density dependence, whereas the mass weighting simply gives more weight to cells that contain more gas mass. The change in weighting places slightly relatively more weight on the warmer bulk component of the gas at large radii, decreasing the difference between  $T_{\text{sp,all}}$  and  $T_{\text{sp,bulk}}$ .

In summary, substructures lead to a change in the average normalized temperature profile at most 10% at  $r/R_{500c} = 1.5$  from  $z = 0.7$  to  $z = 0$ , regardless of the weighting schemes.

#### 4.5. Effects of Non-Equilibrium Electrons

The X-ray temperature is sensitive to the thermal energy of electrons in the ICM plasma. However, since the equilibration time of electrons and ions can be comparable to the Hubble time in the low-density regions in the outskirts of galaxy clusters (Spitzer 1962; Rudd & Nagai 2009), the ICM temperature derived using X-ray observation could be biased low.

The temperature bias from non-equilibrium electrons also depends on the mass accretion rate and the mass of cluster

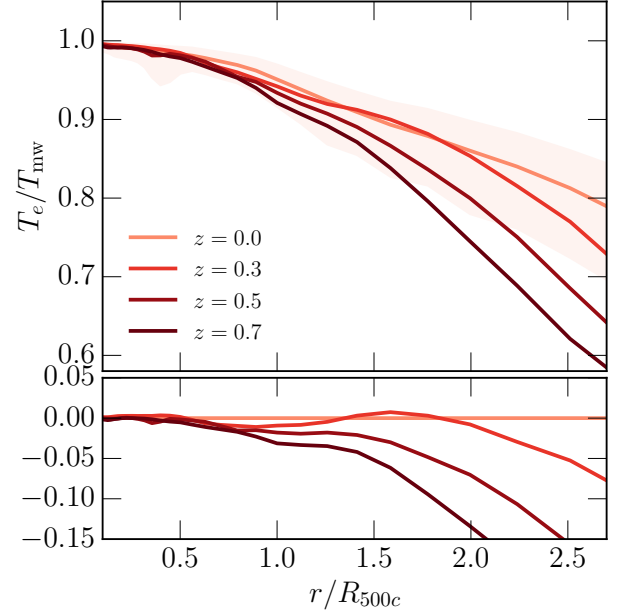


FIG. 6.— Top panel: Average ratio of the mass-weighted electron temperature,  $T_e$ , to the mass-weighted mean gas temperature,  $T_{\text{mw}}$ , as a function of the cluster-centric radius at different redshifts:  $z = 0.0, 0.3, 0.5, 0.7$ . The shaded region indicates  $1\sigma$  scatter in the  $z = 0$  profile. Bottom panel: the fractional evolution in  $T_e/T_{\text{mw}}$  at high redshifts relative to  $z = 0$ .

(Avestruz et al. 2015). On average, high redshift clusters have higher mass accretion rates, which magnifies the bias. However, high redshift clusters have lower average masses. The shorter Coulomb equilibration timescale of the lower temperature gas in less massive clusters therefore counteracts the effect of higher mass accretion rates in high redshift clusters. Figure 6 illustrates the net effect, where we show profile of the ratio of the electron temperature and the total gas temperature. We thus conclude that the evolution between  $z = 0$  and  $z = 0.7$  is less than 5% up to  $r/R_{500c} \approx 1.5$ .

#### 4.6. Effects of Baryonic Physics

Although the effects of baryonic heating and cooling processes are expected to be small in the outskirts of galaxy clusters, dissipative processes can potentially introduce additional physical scales that can lead to breaking of self-similarity in the ICM properties. To assess these effects, we analyze a re-simulation of the *Omega 500* box that includes radiative cooling, star formation, and supernova feedback (CSF). Since our CSF simulation does not include feedback from active galactic nuclei, this simulation suffers from the well-known “over-cooling” problem. Due to overcooling, too many stars form in the cluster core, compared with observations, and the simulation overestimates the impact of baryonic effects. The results from our CSF simulations should therefore provide an *upper* limit to the role of cooling and star formation.

Figure 7 shows the evolution of the ICM temperature profiles in the CSF simulation. The normalized mass-weighted temperature,  $\tilde{T}_{\text{mw}}$ , at  $r/R_{500c} \gtrsim 0.1$  evolves by about 20% over the redshift range of  $0 \leq z \leq 0.7$ , which is roughly consistent with the evolutionary trend seen in the NR run. The non-thermal temperature profiles,  $\tilde{T}_{\text{nt}}$ , in the CSF run (dotted lines in the upper panel of Figure 7) show a higher normalization in the inner regions compared to their NR counterparts, due to rotational gas motions induced by strong gas cooling in the

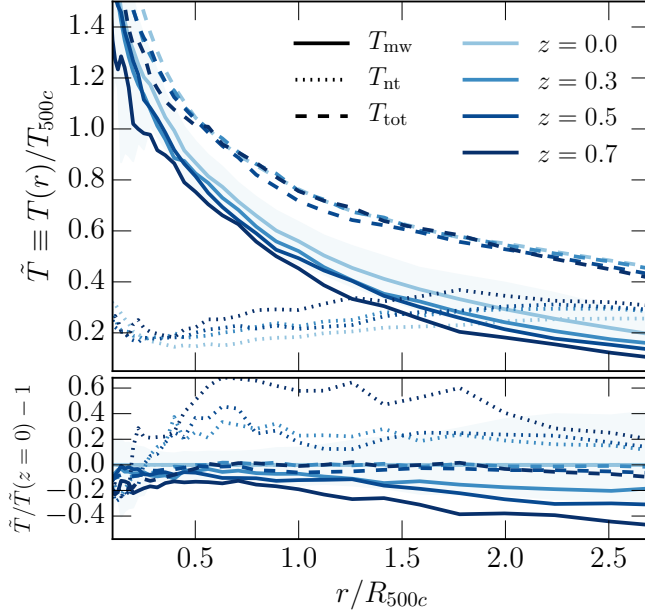


FIG. 7.— Similar to Figure 3, showing the evolution of the temperature profiles for the simulated clusters with radiative cooling, star formation, and supernova feedback. See the figure caption of Figure 3 for the descriptions of panels and line types.

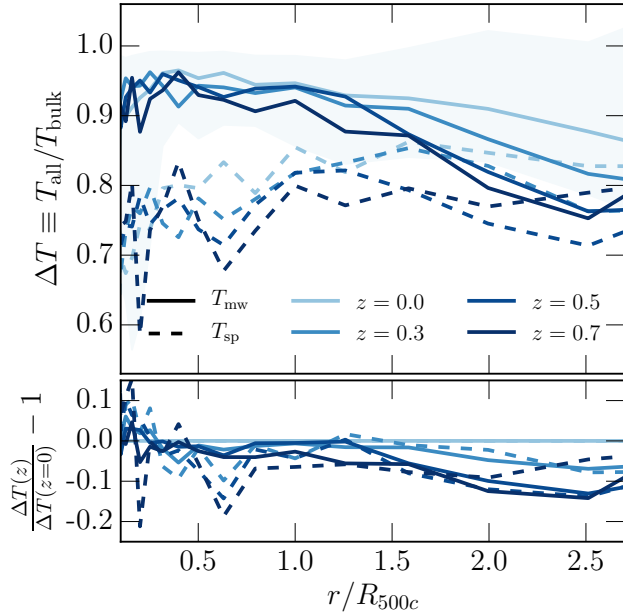


FIG. 8.— Same as Figure 5 for the CSF simulation.

CSF run (see e.g., Lau et al. 2011). Despite the effects of baryonic physics on the ICM temperature profiles, the total temperature profile in the CSF run remains self-similar in the regions  $0.2 \leq r/R_{500c} \leq 2.5$ .

Figure 8 shows the temperature ratio  $\Delta T \equiv T_{all}/T_{bulk}$  in the CSF simulation. Similar to the results for the NR case in Figure 5, this ratio shows little evolution for  $r/R_{500c} \lesssim 1.5$  for both mass-weighted (solid lines) and X-ray spectral-weighted

temperatures (dashed lines). In fact, this effect is smaller in the CSF run than in the NR run, with only  $\lesssim 15\%$  change between  $0 \leq z \leq 0.7$ .

The profiles of both  $\Delta T_{mw}$  and  $\Delta T_{sp}$  have lower normalizations in the CSF clusters than in the NR clusters, since gas cooling in dense, gaseous substructures leads to lower temperatures in the CSF run. Unlike the NR profiles,  $\Delta T_{sp}$  at  $r/R_{500c} \lesssim 1.5$  in the CSF run has a significantly lower normalization than the profiles of  $\Delta T_{mw}$  at each redshift, particularly in the inner radii. Here, the spectroscopic weighting gives more weights to substructures in the ICM that are cooler and denser in the CSF run. Nevertheless, the contribution of substructures introduces little additional evolution in the ICM temperature.

Thus, even in the presence of baryonic physics, the thermal temperature evolution is mainly driven by the redshift-dependent non-thermal gas motions, not by the increased amount of gaseous substructures.

## 5. SUMMARY AND DISCUSSIONS

We have investigated the origins of the evolution in the ICM temperature profiles in the outskirts of galaxy clusters using a mass-limited sample of 65 galaxy clusters extracted from the *Omega500* NR and CSF hydrodynamical cosmological simulations. Our key findings are summarized below:

- The non-thermal pressure due to gas motions is the primary mechanism for driving the evolution of the ICM temperature profiles in the outskirts of galaxy clusters, producing a change in the ICM temperature by 30% at  $R_{500c}$  relative to the prediction of the self-similar model.
- Gaseous substructures associated with infalling satellites and penetrating filaments contribute to the evolution of the temperature profiles by  $\lesssim 10\%$  at  $R_{500c}$ , and it is subdominant to the evolution due to thermalization of gas motions.
- The effects of spectral-weighted temperature, and the effects of non-equilibrium electrons, contribute to less than 10% in the evolution of the ICM temperature. Baryonic physics do not alter these conclusions.

These results suggest that the recently observed temperature evolution in the outskirts of galaxy clusters by McDonald et al. (2014) is primarily due to the evolution of the non-thermal pressure profiles in the ICM, in contrary to their original interpretation of “superclumping”.

Our work further suggests that it may be possible to mitigate and control the departure from the self-similar evolution. First, we find that an appropriate choice of cluster mass and radius can mitigate departures from self-similarity in the temperature profile. The reference density that scales with accretion in the outskirts, 200 times the mean background density, best captures self-similar evolution in the temperature profile in the outskirts. Other reference densities with respect to the mean density, e.g.,  $\rho_{1600m}$  and  $\rho_{500m}$ , do not scale as well. Second, we find that the “total” temperature, which is the sum of thermal and non-thermal gas energies, exhibits a remarkable degree of self-similar evolution when scaled with respect to the critical density.

In practice, while the thermal component of the ICM can be directly imaged using X-ray and SZ observations, emerging high-angular resolution X-ray and SZ imaging observations can measure fluctuations in the ICM properties, which

are sensitive to the level of non-thermal pressure due to gas motions (e.g., Schuecker et al. 2004; Khatri & Gaspari 2016). Future X-ray observatories, such as *Athena+*, also promise to provide direct measurements of gas motions in the ICM through Doppler broadening of Fe lines.

Note that our simulations do not include other scale-dependent plasma physics, such as thermal conduction and magnetic fields. However, we expect these to have subdominant effects. Thermal conduction in the cluster outskirts is believed to be ineffective due to the long conduction timescales of the diffuse low temperature outskirt gas (e.g., McCourt et al. 2013). While magnetic fields can drive gas turbulence through magnetothermal instability (MTI) (Parrish et al. 2012), McCourt et al. (2013) shows MTI-driven turbulence to be subdominant to the gas motions driven by mergers and accretion for realistic cluster mass accretion histories. Therefore, neither thermal conduction nor magnetic fields are likely to play significant roles in the evolution of temperature profiles in cluster outskirts. Other effects, such as pressure provided by cosmic rays, can in principle alter ICM properties in cluster outskirts. We leave the study of the effects of these plasma physics for future work.

To advance our understanding of ICM properties and their evolution in cluster outskirts, future work should focus on (1) improving theoretical modeling of both thermal and non-thermal components including turbulence, cosmic rays, magnetic fields, and their interactions; (2) deriving observational constraints on the non-thermal temperature/pressure in the ICM based on pressure fluctuations as well as direct measurements with the upcoming X-ray missions; and (3) developing techniques to control the still poorly understood astrophysical uncertainties and their impact on cluster-based cosmological inferences.

This work is supported by NSF grant AST-1412768, NASA ATP grant NNX11AE07G, NASA Chandra Theory grant GO213004B, the Research Corporation, and by the facilities and staff of the Yale Center for Research Computing. CA acknowledges support from the Fisk-Vanderbilt Dissertation Completion Award, the Kavli Institute of Cosmological Physics, the Enrico Fermi Institute at the University of Chicago, and the University of Chicago Provost's Office.

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